



AFRL-AFOSR-VA-TR-2017-0031

Reaching higher Gamma in ultracold neutral plasmas through
disorder-induced heating control

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Final Report

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Final report: Achieving higher Gamma in ultracold neutral plasmas through disorder-induced heating control

S. D. Bergeson

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June 28, 2016

Abstract

This is the final report on project FA9950-12-1-0308, “Reaching higher Gamma through disorder-induced heating control.” Highlights from the grant include making the first ion temperature measurements in a multiply-ionized ultracold neutral plasma (Ca/Ca⁺), making the first measurements of the ion temperature in a plasma that evolves from a dense Rydberg gas, and starting work on the first dual-species MOT and plasma.

This project included three major activities. The first was to explore the possibility of increasing the strong-coupling parameter in an ultracold neutral plasma by sequentially ionizing to higher ionization states. This work was motivated by a calculation indicating that it would be possible to quadruple the coupling parameter. The second major activity was to explore the possibility of using the Rydberg excitation blockade to pre-order the neutral gas before ionization. The third major activity was to build a new experiment to study energy relaxation in a dual-species ultracold neutral plasma.

This document summarizes achievements at Brigham Young University during the award FA9950-12-1-0308 from June 1, 2012 to May 31, 2016. The primary focus of this effort was to find ways to increase the value of the strong coupling parameter in ultracold neutral plasmas. This parameter is defined as the ratio of the nearest-neighbor Coulomb energy to the average ion kinetic energy in the plasma,

$$\Gamma = \frac{Z^2 e^2}{4\pi\epsilon_0 a_{\text{ws}}} \frac{1}{k_B T}, \quad (1)$$

where Z is the ion charge state, $a_{\text{ws}} = (3/4\pi n)^{1/3}$ is the Wigner-Seitz radius, n is the ion (number) density, and T is the ion temperature.

The value of the strong-coupling parameter is limited by disorder-induced heating in ultracold neutral plasmas. This heating occurs as the ions relax towards equilibrium. The plasma ions have essentially no kinetic energy when they are first ionized. However, due to the random spatial distribution in the atom trap, the ions have a comparatively large value of electrical potential energy. Energy relaxation converts the potential energy to kinetic energy and the plasma ions heat up dramatically. In our experiment, laser-cooled atoms ($T \sim 1$ mK) heat to temperatures near 2 K in a time frame of 100 to 500 ns.

Achieving higher values of the strong coupling parameter remains a major priority for this field. Molecular dynamics simulations show that thermodynamic and kinetic properties of these plasmas scale with the strong-coupling parameter. However, connecting these computationally-intensive simulations with extensions of kinetic theories remains a challenge. Carefully diagnosed and high accuracy experiments that study the characteristics of neutral plasmas over a range of strong-coupling parameter values can help in this effort. Because plasma properties scale with Γ , measurements in ultracold neutral plasmas can inform the diagnostics of high-energy-density plasmas. Better understanding of collision rates, equilibration, and energy transport in warm dense matter may lead to important technological and scientific advances in fusion class plasmas. Given the failure to achieve ignition at NIF, a better understanding of strongly-coupled neutral plasmas remains a national priority.

Table 1: Undergraduate students supported by this project. The titles of the senior theses written by these students is also give.

| Student name | Senior thesis title | Post-BYU employment |
|--------------------|--|--|
| Meredith Gold Dahl | Determining the accuracy of a partially-stabilized frequency comb | Grad. student at U. Rochester |
| Daniel Woodbury | Construction of a compact two-dimensional magneto-optical trap for a cold calcium beam | Grad. student at U. Maryland |
| Joshua Wilson | Ultracold neutral plasma physics at room temperature | Grad. student at Penn State |
| Alex Erikson | A permanent magnet Zeeman slower (in process) | Medical school, Fall 2017 |
| Nicholas Harrison | Radius and intensity dependence of laser plasma expansion | Private sector |
| Daniel Crunkleton | Strong field ionization of neutral strongly-coupled plasmas in a gas jet | USAF |
| Stephen Rubber | Frequency locking circuits | Sandia National Lab (starting graduate school at BYU 2016) |

1 Personnel

This grant supported one graduate student, Mary E. Lyon. Dr. Lyon received her Ph.D. in December 2014. She is the lead author on five of the six archival publications from the grant. After receiving her degree, she accepted a post-doctoral research position at the Joint Quantum Institute at the University of Maryland.

This grant also supported seven undergraduate students At Brigham Young University. They are listed in Table 1. This research project is continuing under NSF support. This fall two graduate students (Stephen Rupper and Tucker Sprenkle) and three undergraduate students (Heather Longstaff, Quin McNight, and Michael Peterson) will be working in my lab on this and related projects.

2 Publications

During the grant, six peer-reviewed journal articles were published. During this past year, four conference presentations were also made. These are enumerated in Tables 2 and 3.

Table 2: Peer-reviewed publications from this grant.

| | |
|----|---|
| 1. | M. Lyon, S. D. Bergeson, G. Hart, and M. S. Murillo, "Strongly-coupled plasmas formed from laser-heated solids," Scientific Reports 5, 15693 (2015), DOI:10.1038/srep15693 |
| 2. | S. D. Bergeson, M. Lyon, J. B. Peatross, N. Harrison, D. Crunkleton, J. Wilson, S. Rupper, A. Diaw and M. S. Murillo, "A neutral strongly coupled laser-produced plasma by strong-field ionization in a gas jet," AIP Conf. Proc. 1668, 040001 (2015), December 2014, Takamatsu, Japan, DOI:10.1063/1.4923114 |
| 3. | M. Lyon and S. D. Bergeson, "Towards stronger Coulomb coupling in an ultracold neutral plasma," Contrib. Plasma Phys. 55, 399-406 (2015), DOI:10.1002/ctpp.201400097 |
| 4. | M. Lyon, S. D. Bergeson, A. Diaw, and M. S. Murillo, "Using higher ionization states to increase Coulomb coupling in an ultracold neutral plasma," Phys. Rev. E 91, 033101 (2015) |
| 5. | M. Lyon and S. D. Bergeson, "Precision spectroscopy using a partially stabilized frequency comb," Appl. Opt. 53, 5163-5168 (2014) |
| 6. | M. Lyon, S. D. Bergeson and M. S. Murillo, "The limit of strong ion coupling due to electron shielding," Phys. Rev. E 87, 033101 (2013) |

3 Higher Gamma using electron screening

The first publication in this grant explored the possibility of using electron screening to reduce the temperature of the ions and thereby increase the strong coupling parameter. In previous work in our lab we showed that the electron screening results in very low temperatures. Working with Michael Murillo, we showed that unfortunately the electron screening reduces the nearest-neighbor potential energy by the same amount. Therefore the physical value of the strong coupling parameter remains unchanged. It is important to understand this point. Although some groups report somewhat higher values of Γ , these can only be viewed as a scaled inverse ion temperature and not a physically meaningful ratio of potential-to-kinetic energy.

Publications:

- M. Lyon, S. D. Bergeson and M. S. Murillo, “The limit of strong ion coupling due to electron shielding,” Phys. Rev. E 87, 033101 (2013)

4 Sequential ionization of ultracold plasma ions

A simulation published in 2007 by Michael Murillo showed that the quasi-coherent kinetic energy oscillations of ions in ultracold neutral plasmas could be used to increase the strong coupling parameter by a factor of 4 (see Eq. 1 and Fig. 1).

We built an experiment to explore this possibility in neutral Calcium. We used five pulsed lasers to reach the second ionization stage. While the disorder-induced heating may not increase when the second ionization event occurs, the electron temperature increases significantly. This increases the plasma expansion rate, as shown in Fig. 2.

One of the limitations in this approach is that the strong laser fields required for ionization Stark-shift the intermediate energy levels out of resonance with the excitation lasers. The maximum achievable second ionization fraction was therefore 35%, consistent with a rate-equation model for the excitation. The limited second-ionization resulted in some additional ion heating, as verified by molecular dynamics simulations of the experiment (see Figs. 3 and 4).

Publications:

- M. Lyon and S. D. Bergeson, “Towards stronger Coulomb coupling in an ultracold neutral plasma,” Contrib. Plasma Phys. 55, 399-406 (2015)
- M. Lyon, S. D. Bergeson, A. Diaw, and M. S. Murillo, “Using higher ionization states to increase Coulomb coupling in an ultracold neutral plasma,” Phys. Rev. E 91, 033101 (2015)

5 Generating spatial order via the Rydberg excitation blockade

Several demonstrations of the Rydberg blockade have been published in ultracold atom experiments. The blockade occurs when the atom-atom interaction results in an energy level shift that is greater than linewidth of both the laser and the atomic level. At long range, the energy level shift can be described as a van der Waals interaction between excited atoms using a relatively simple atomic theory. Most of the research in

Table 3: Contributed conference presentations from this grant during the past year.

1. (Invited) S. D. Bergeson, “What 1-Kelvin plasmas can tell you about thermonuclear fusion,” APS 4-Corners Meeting, Tempe AZ, October 2015
 2. (Invited) S. Bergeson, “Some progress towards an ultracold Ca/Yb plasma,” AFOSR workshop on ultracold neutral plasmas, Santa Fe, NM, May 2016
 3. M. Lyon, S. Bergeson, G. Hart, M. Murillo, “Strongly-coupled plasmas formed from laser-heated solids,” DAMOP, Providence RI, May 2016
 4. S. Bergeson and M. Lyon, “Measurements of the ion velocity distribution in an ultracold neutral plasma derived from a cold, dense Rydberg gas,” DAMOP, Providence RI, May 2016
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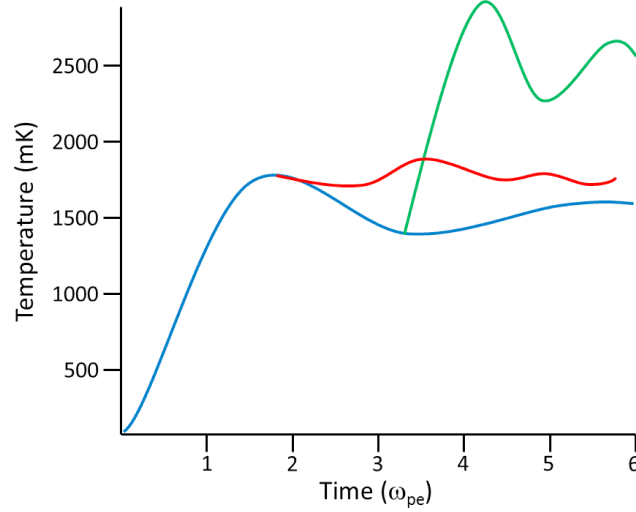


Figure 1: Temperature as a function of scaled time for ions in an ultracold neutral plasma. The blue line shows the temperature evolution due to disorder-induced heating. The red line shows the predicted temperature evolution if the ions are promoted to the second ionization state at the peak of the blue curve. In this case, no additional disorder-induced heating occurs because ionization occurs at the minimum in the ion potential energy evolution. The green line shows the predicted temperature increase when the ions are promoted to the second ionization state at later times. From M. S. Murillo, Phys. Plasmas 14, 055702 (2007).

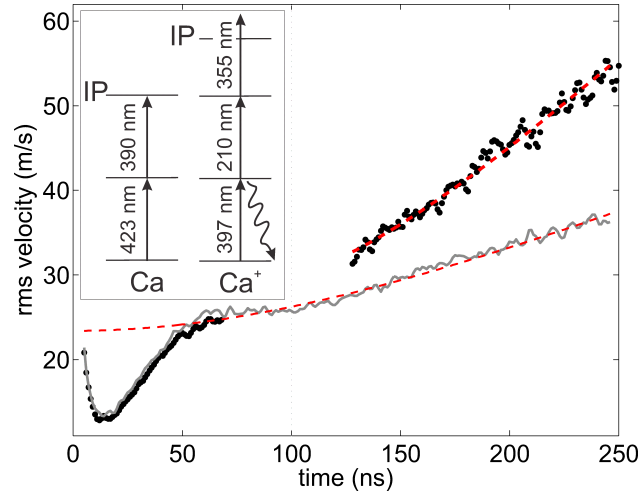


Figure 2: RMS ion velocity in an ultracold neutral calcium plasma. The inset shows the excitation pathway. The velocity distribution was probed using laser-induced fluorescence at 397 nm on the residual Ca^+ ions. The second ionization event occurred at 100 ns for this data. Scattered light, optical pumping, and spontaneous emission prevented meaningful velocity measurements closer than ± 30 ns after the ionization event. The gray line is the rms velocity without the second ionization event. The black dots represent the rms velocity when the second ionization event occurs. The red lines are fits of the data to expansion models. From M. Lyon, S. D. Bergeson, A. Diaw, and M. S. Murillo, Phys. Rev. E 91, 033101 (2015).

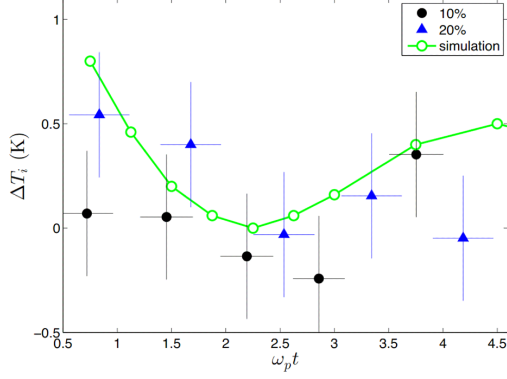


Figure 3: Extracted increase in the ion temperature as a function of time delay between the first and second ionization event. The green line shows the predicted increase in temperature from a simulation of the experiment. From M. Lyon, S. D. Bergeson, A. Diaw, and M. S. Murillo, Phys. Rev. E 91, 033101 (2015).

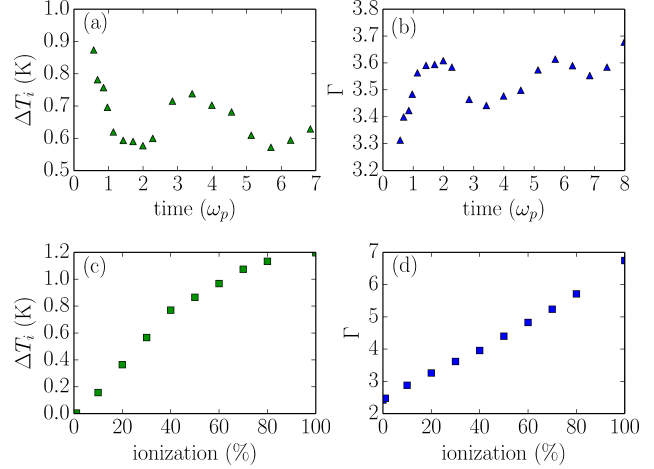


Figure 4: Molecular dynamics results showing the increase in temperature and also the value of the strong-coupling parameter Γ as a function of ionization fraction. From M. Lyon, S. D. Bergeson, A. Diaw, and M. S. Murillo, Phys. Rev. E 91, 033101 (2015).

this area occurs in this low-energy regime. That research is generally motivated by applications in quantum information.

In certain configurations, the long-range repulsive interaction between Rydberg atoms is used to generate spatial order in neutral gases. While most demonstrations of this effect have been made using degenerate quantum gases or atoms in optical dipole traps, a few publications suggest that spatial ordering might be achievable in a magneto-optical trap like the one used in our lab. If the Rydberg system could be rapidly ionized, the spatial ordering from the blockade is predicted to be sufficient to increase the value of the strong-coupling parameter to $\Gamma \leq 30$.

We explored the possibility of using the Rydberg blockade to generate a spatially ordered atomic sample. We used an excitation scheme that is typical of Rydberg excitation experiments (see Fig. 5). Our initial work using cw laser excitation proved to be insufficient to achieve enough excitation before the calcium atoms moved significantly. When the atoms move during the excitation pulse, they collide with neighboring atoms and collisionally ionize, thereby compromising the blockade effect.

We further explored the possibility of using ns-duration pulsed lasers to achieve the Rydberg blockade. Typical excitation efficiency measurements are shown in Fig. 6 for excitation to the $n = 30$ state. We measured these kinds of efficiency curves for a number of different Rydberg levels. The results are shown in Fig. 7.

Following excitation, we used a weak cw laser tuned to the ion resonance transition at 397 nm to probe the velocity distribution of the Rydberg atoms. Results are shown in Fig. 8. The probe laser beam caused ionization of the Rydberg atoms due to core-interaction. Therefore we introduced a variable time delay, between 0 and 10 μ s in order to let the Rydberg system evolve unperturbed before probing the system. Any reduction in disorder-induced heating should be apparent in the first few μ s of the data. However, a reduction is not clearly evident and further work is required to understand the system in detail. In particular, excitation with the large Rabi frequencies necessary to achieve collective excitation in a few ns is probably inadequately described by a simple van der Waals analysis of the Rydberg-Rydberg atom interaction. Full molecular potential curves need to be calculated and analyzed for this project to move forward.

Publications:

- S. D. Bergeson and M. Lyon, “Measurements of the ion velocity distribution in an ultracold neutral plasma derived from a cold, dense Rydberg gas,” arXiv:1601.07439.

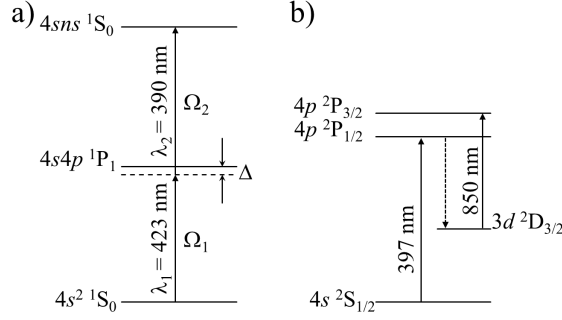


Figure 5: Partial energy level diagram for calcium. a) The two-photon Rydberg excitation pathway using laser pulses at 423 and 390 nm. b) The excitation and fluorescence scheme used to diagnose the Ca^+ ions formed after Rydberg excitation.

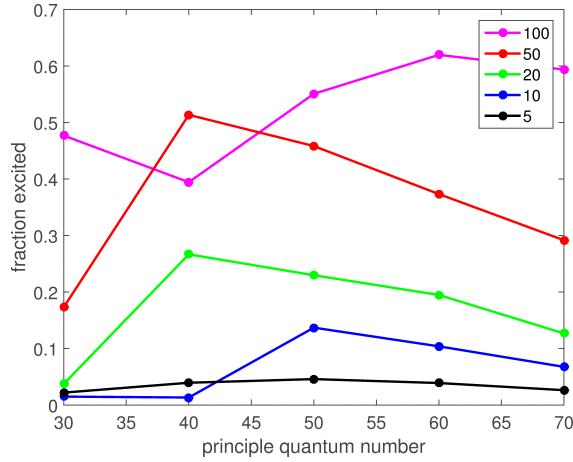


Figure 7: Rydberg atom excitation efficiency for a range of different principle quantum numbers and a range of different laser frequencies. These data are suggestive of blocked excitation. However more work needs to be done to understand the excitation dynamics. The densities and excitation energies are high enough that a simple van der Waals treatment is probably insufficient. The legend indicates the excitation laser intensity in units of 10^7 mW/cm^2 . From S. D. Bergeson and M. Lyon, arXiv:1601.07439.

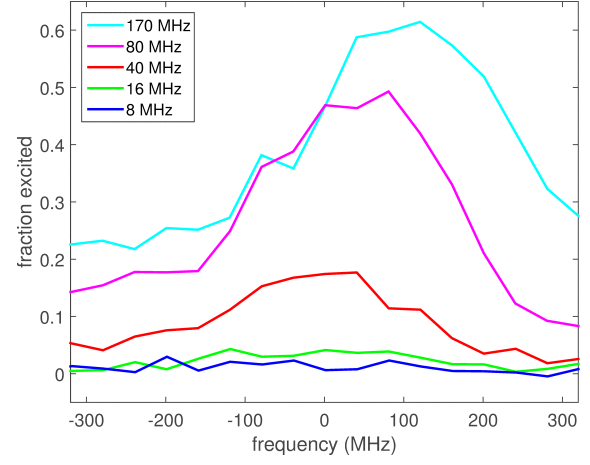


Figure 6: Rydberg excitation efficiency as a function of Ω_2 and fixed $\Omega_1 = 350 \text{ MHz}$ for a principle quantum number of 30. As the laser intensity increases (Ω_2 increases), the excitation efficiency also increases. At high intensities the Rydberg excitation frequency is Stark-shifted by the pulsed laser.

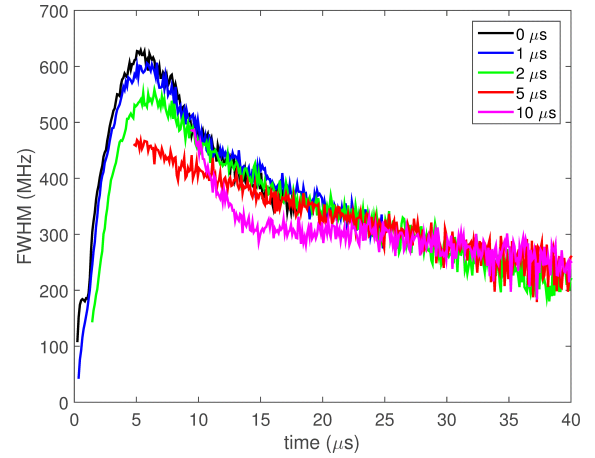


Figure 8: RMS velocity distribution of the Rydberg atoms/plasma generated after excitation to $n = 50$ at high laser power shown in Figure 7. Because of the ionization resulting from core-excited Rydberg atoms, a time delay was introduced in between Rydberg excitation and the probe laser. Evidence of reduced disorder-induced heating should be apparent in the first 1 or 2 μs of the data. However, any reduction is not clear. From S. D. Bergeson and M. Lyon, arXiv:1601.07439.

6 Dual-species plasma work

During a one-year extension to this project, we built a dual-species MOT for Yb and Ca. These atoms differ from one another by a factor of 4 in mass. The plan is to ionize both of these species and to study energy relaxation and velocity diffusion. We have trapped Ca and Yb atoms simultaneously in our MOT. An initial study of the trap losses indicate that these atoms do not interact strongly. There is no Yb-induced loss in the Ca MOT and no Ca-induced loss in the Yb MOT. In other dual-species MOTs, simultaneous trapping of different atoms is often impractical because the losses are too great. However, there is no hyperfine splitting in Ca-40, and the hyperfine splitting in Yb is all in the excited state. This bodes well for our future work.

The atomic densities in the MOT are approximately 10^{16} cm^{-3} . As of this writing, work is underway to increase the number of atoms in the MOT and to optimize trapping parameters.

This experiment requires four frequency-doubled ti:sapphire lasers, all of which are in place in our lab. It also requires four pulsed lasers for ionization, three of which are in our lab. The final one should be in place before the end of the year.

This work will continue with funding from the joint NSF/DOE plasma physics program. This is a collaborative research proposal that includes Professor Michaela Kleinert at Willamette University in Oregon, Michael Murillo at the New Mexico Consortium, and Scott Bergeson at Brigham Young University.

1.

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Grant/Contract Number**AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".**

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Scott Bergeson

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Abstract

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Archival Publications (published) during reporting period:

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2. S. D. Bergeson, M. Lyon, J. B. Peatross, N. Harrison, D. Crunkleton, J. Wilson, S. Rupper, A. Diaw and M. S. Murillo, "A neutral strongly coupled laser-produced plasma by strong-field ionization in a gas jet," AIP Conf. Proc. 1668, 040001 (2015), December 2014, Takamatsu, Japan, DOI:10.1063/1.4923114
3. M. Lyon and S. D. Bergeson, "Towards stronger Coulomb coupling in an ultracold neutral plasma," Contrib. Plasma Phys. 55, 399-406 (2015), DOI:10.1002/ctpp.201400097
4. M. Lyon, S. D. Bergeson, A. Diaw, and M. S. Murillo, "Using higher ionization states to increase Coulomb coupling in an ultracold neutral plasma," Phys. Rev. E 91, 033101 (2015)
5. M. Lyon and S. D. Bergeson, "Precision spectroscopy using a partially stabilized frequency comb," Appl. Opt. 53, 5163-5168 (2014)
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7. S. D. Bergeson and M. Lyon, "Measurements of the ion velocity distribution in an ultracold neutral plasma derived from a cold, dense Rydberg gas," arXiv:1601.07439 (2016)

2. New discoveries, inventions, or patent disclosures:

Do you have any discoveries, inventions, or patent disclosures to report for this period?

No

Please describe and include any notable dates

Do you plan to pursue a claim for personal or organizational intellectual property?

Changes in research objectives (if any):

A one-year extension was granted that allowed us to build a dual-species Yb/Ca MOT. This is a new extension of the originally proposed work. It is major stepping stone towards realizing a dual-species ultracold neutral plasma.

Change in AFOSR Program Manager, if any:

None

Extensions granted or milestones slipped, if any:

A one-year extension was granted that allowed us to build a dual-species Yb/Ca MOT. This is a major stepping stone towards realizing a dual-species ultracold neutral plasma.

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, \$K)

| | Starting FY | FY+1 | FY+2 |
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